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MAGNETIC RESPONSE OF AN ORGANISM AND ITS SOLAR RELATIONSHIPS [1]

F. A. BROWN, JR., W. J. BRETT, M. F. BENNETT AND F. H. BARNWELL [2]

Departments of Biological Sciences, Northwestern University, Indiana State Teachers College, and Sweet Briar College, and The Marine Biological Laboratory, Woods Hole, Mass.

It has become increasingly evident in recent years that the living organism is sensitive to fluctuations in still unidentified geophysical factors, in addition to those factors with which physiologists and ecologists have customarily concerned themselves in the past (Brown, 1959a). Such obvious environmental factors as temperature, light, humidity, gravity, pressure, and sound, are clearly ones toward which it is usually highly important that organisms exhibit immediate adaptive responses. Correspondingly, it is well-known that living things, in general, have their behavior and basic physiology dominated in terms of response to them.

On the other hand, organisms in environments held constant with respect to all these obvious factors still exhibit physiological and behavioral fluctuations correlated with fluctuations in other such geophysical parameters as atmospheric pressure, atmospheric temperature, primary cosmic radiation, and general background radiation, including both their regular atmospheric tidal changes, and their large, weather-related, essentially aperiodic, changes. The correlations are of such character as to indicate clearly that other and yet unidentified factors are also effective for organisms. These less obvious environmental factors appear able to induce or trigger relatively large biological alterations, not uncommonly into the range of 30% or more in their deviation from longer-term mean values. In general, it does not appear adaptive that organisms should permit physiological processes to be regulated by these subtle factors instead of by the more obvious environmental ones, and not unexpectedly, therefore, homeostatic mechanisms seem normally to be continuously operative in reaction to the alterations induced by them.

In two particular associations, however, such subtle environmental factors and their fluctuations may possess clear adaptive value, and there are good reasons to postulate that organisms have evolved physiological means for utilizing this value.

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One of these is in temporal orientation, or the timing of the well-known temperature-independent solar-daily, lunar-daily, synodic monthly, and annual periodicities that commonly persist in complete constancy of all factors to which the organisms are usually deemed sensitive. Indeed, it has been shown possible to account for all the many and peculiar described properties of these long-cycle persistent rhythms in terms of periodicities effected by the subtle factors (Webb and Brown, 1959; Brown, 1959). The second association relates to spatial orientation, particularly as it pertains to the periodic migrations of organisms for feeding and breeding, and especially to the navigational aspects of the phenomenon.

Suggesting a role of subtle environmental factors in animal navigation is the demonstration in recent years of a very close interrelationship between the phenomena of temporal and spatial orientation of animals (Hoffman, 1954; Pardi and Grassi, 1955; Renner, 1959) quite as our own spatial orientation may depend on relationships to sun, moon or the constellations as a function of time. In both of these associations, temporal and spatial orientations, control by the obvious factors, when available, may be the dominating consideration. However, a number of observed characteristics of these phenomena appear inadequately accounted for in these terms alone. Such problems might be greatly simplified were it learned that organisms had available additional information.

On the one hand, it is obvious from available evidence that at least some subtle geophysical factors are perceived by organisms. And yet, on the other hand, cursory examinations for the biological effectiveness of changes in various ones of these within essentially their natural range have in the past yielded generally negative results. Therefore, it seems obvious that the question must be more critically re-examined. The work about to be described is the consequence of a brief, intensive re-examination for possible response to the magnetic field. In this study, reported earlier briefly (Brown, Brett and Webb, 1959; Brown, Bennett and Brett, 1959; Brown, Webb, Bennett and Barnwell, 1959), not only is it apparent that an organism responds significantly to the changes in the magnetic field through alterations in its spatial orientation, but that the response is intimately associated with the mechanism of temporal orientation of organisms quite as might be expected were the magnetic orientation to possess usefulness to the organism.

Methods and Materials

The common mud-snail, *Nassarius obsoleta,* was used in this study. Collections were made at Chappaquoit Beach, West Falmouth, Massachusetts, at approximately weekly intervals, and the stock collections were maintained on a table in running sea-water in the ordinary daily illumination changes of the laboratory.

Simple equipment (Fig. 1) was constructed to determine the degree of right and left turning of snails as they emerged from a narrow corridor into a constant, symmetrically illuminated field. The apparatus consisted of an aluminum, funnel-shaped corral fastened in an 8-inch crystallizing dish set upon a polar-coordinate grid with the opening of the funnel over the center of the grid. A circle of 3 cm. radius was drawn. The grid was ruled into 22.5° sectors, and the long axis of the corridor was accurately aligned with the center of the sector labelled zero. Since the sizes of the snails varied from nearly the width of the corridor to half of that value, even snails following one or the other corridor wall and continuing on a straight path would, after 3 cm., lie in the zero sector. Successive sectors to the right were given numbers + 1 through + 4, and to the left, − 1 through − 4. This apparatus was placed on the bottom of a 17 × 12 × 10 inch box, as shown in Figure 2, in such a manner that a 4½-inch round window illuminated by an enclosed 60-watt incandescent lamp and covered with a white diffusing transmitter lay above and slightly ahead of the corridor exit. A hooded window for observing the snail movements, and for re-corraling the snails between the successive runs of ten, was

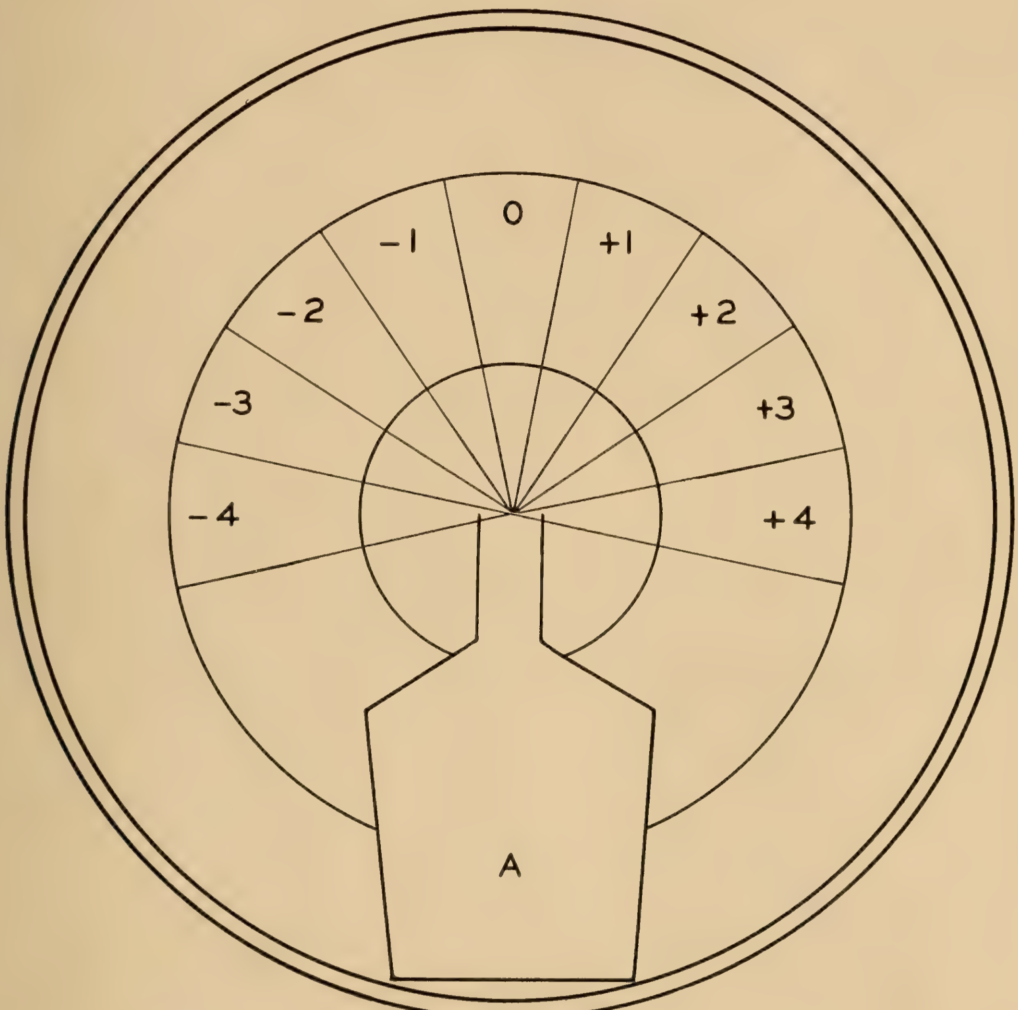

FIGURE 1. Orientation apparatus. View from above of the corral (A) in an 8-inch glass crystallizing dish placed over a polar grid. All dimensions may be scaled from the 3-cm. radius of the innermost circle.

located above and to the rear of the corral. Beneath the box was an adjustable platform with a horizontal turntable upon which an 18-cm. Alnico bar magnet could be easily placed, centered under the corridor exit and orientated in any compass direction, or from which the magnet could be removed quickly. The magnet at 14 cm. below the orientation chamber gave a horizontal intensity (1.5 gausses) only about nine times that of the earth's field in Massachusetts (.17 gauss). Such a weak experimental magnetic field was purposely selected to increase the probability that any response which might be discovered was a naturally occurring phenomenon.

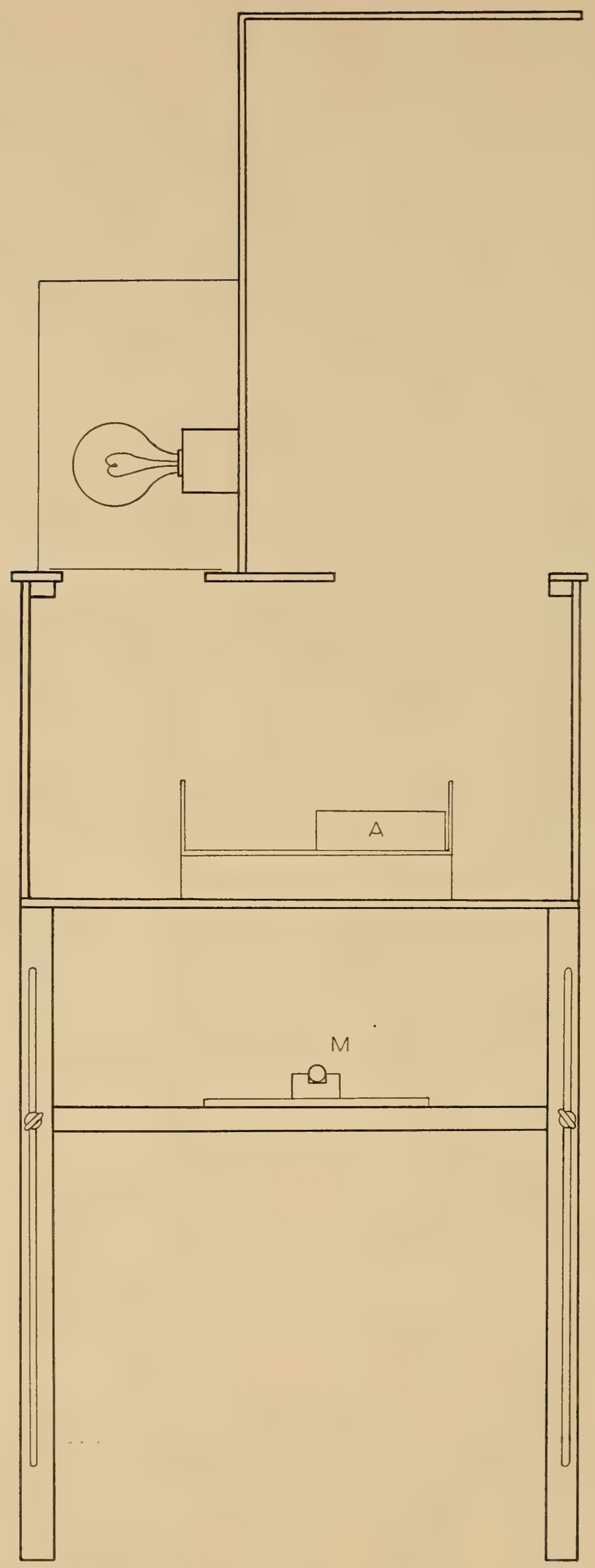

FIGURE 2. Lateral view of the diagrammatically-sectioned wooden orientation apparatus, drawn to scale. A is the corral, M is the bar-magnet.

Such a field strength would be expected to lie within the range of sensitivity of any normally operative responder system which might be present for magnetism. Four identical orientation chambers were available during the study.

The experimental procedures were kept uniform, simple and minimal. The apparatus was always oriented carefully so that the corridor exit was pointed toward the magnetic south. Sea-water to a depth of about 2 cm. was added to the crystallizing dish. Eleven to fifteen snails were dropped into the corral. Each completed experimental series consisted of 60 snail exits, two groups of ten exits without magnet, two groups of ten with the artificially increased magnetic field oriented as the earth's field (with north-seeking pole directed south), and two groups of ten with the north-seeking pole directed west. The first three groups of ten usually consisted of one of each of the three experimental conditions, as did also the last three. The order within the three groups of ten, however, changed continuously. Throughout most of the period of experimentation, the observer was uninformed as to the presence or absence, or orientation, of the magnet. Each snail emergence was accorded one number, that of the sector in which the head, or greater fraction of it, was located at the instant the snail reached the 3 cm. arc.

It is important to note that the method does not involve the determination of any final pathway chosen by the snails; rather, it simply yields a measure of any tendency toward change in direction from the initial path, and the relative degree of this tendency. The use of this kind of measurement appeared to reduce to a minimum obviously erratic, exploratory movements.

It was learned from brief exploratory experiments that the mean path of turning for any given time was not conspicuously influenced by changing the compass direction of orientation of the experimental chamber.

During the two-month period, June 28 to August 29, 1959, inclusive, 564 such series of 60 snail passages were obtained. Series were obtained for all hours of the day from 5 AM through 9 PM, Eastern Standard Time. No single one of these hours of the solar-day was represented by fewer than 9 or by more than 50 series of 60 snail exits.

Results

It was apparent early in the experimentation that the snails, whether controls *without* experimentally imposed magnetic field or experimentals *with* such imposed fields, varied greatly from one time to another in both their spontaneity of activity and their rate of locomotion. This resulted in differences in time for completion of a single series of 60 runs, ranging from about 12 to 60 minutes. Secondly, the pattern of emergences of the snails clearly differed significantly from one time to another under the same experimental conditions. Thirdly, the results of comparisons within single series of 60 runs indicated an influence of the experimental magnetic fields.

Sample patterns of emergence of the snails are illustrated for nine series in Figure 3. These were selected, without reference to time, for the purpose of illustrating the wide variety of results. It is quite evident from this figure that the experimental magnetic fields, even if effective, could not be producing a simple uniform response. As seen from the sample patterns, the introduction of the N–S oriented magnet (B in figure) could, as the average of the two runs of ten snails, be associated with a mean path to left, (*e.g.*, #1, 2, 7, 9) or to the right (*e.g.*, #3,

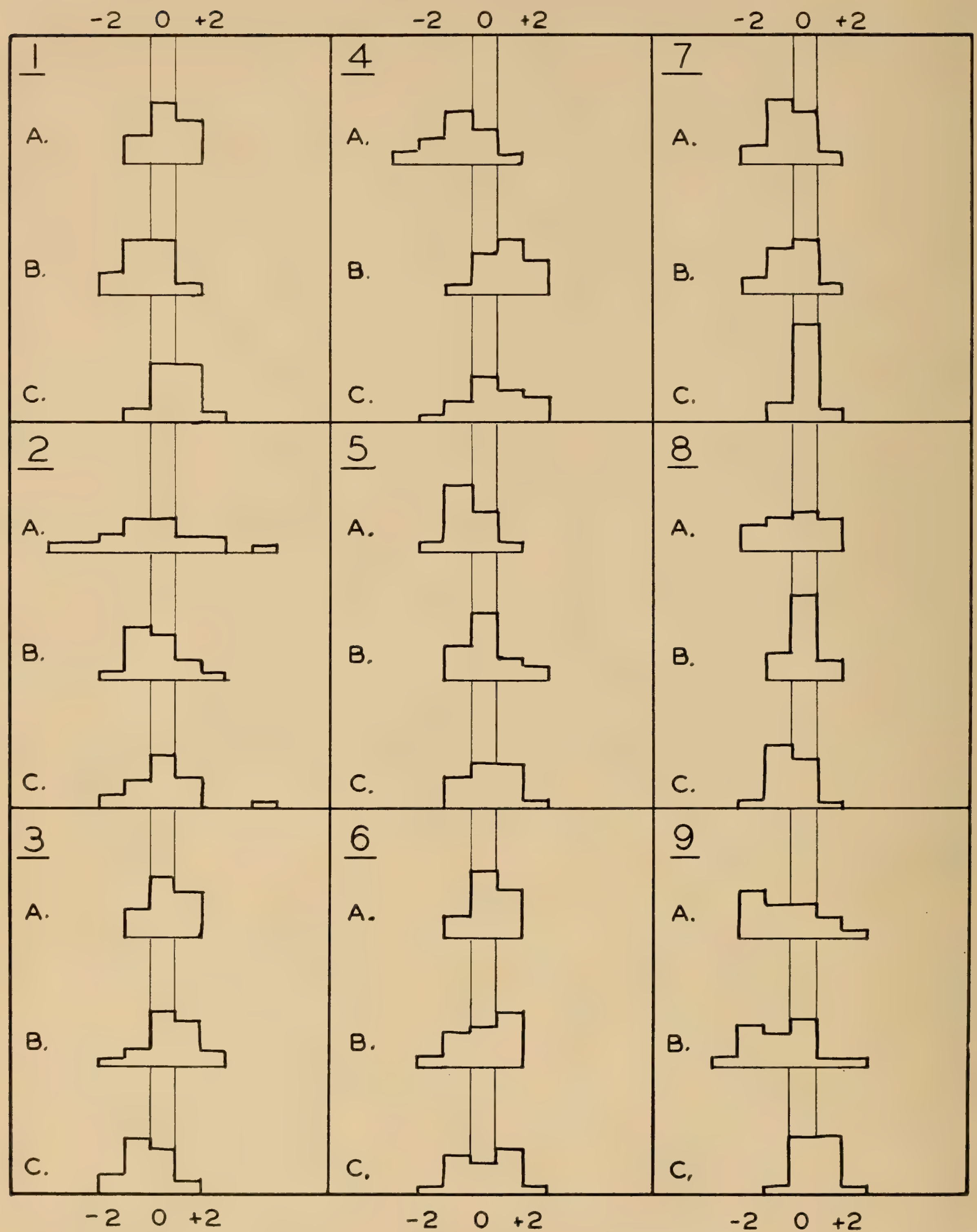

FIGURE 3. The frequency distributions of snail paths found in nine sample series of 60 runs. A, 20 runs in E–W magnet field. B, 20 runs in N–S magnet field. C, 20 control runs only in the earth's (N–S) field. See text for discussion.

4, 8) of the controls. The N–S oriented magnet could appear to effect more dispersion from zero than the controls within the same series (*e.g.*, #3, 7, 9) or less (*e.g.*, #2, 4, 8); it could appear to effect mean paths to right (*e.g.*, #4, 5) or the left (*e.g.*, #1) of the E–W oriented magnetic field (A in figure) or to produce more (*e.g.*, #3, 6) or less (*e.g.*, #2, 8) dispersion than that observed within the same series for the E–W oriented magnet. Comparably, the E–W oriented magnet was associated with patterns to left (*e.g.*, #4, 5, 7, 9) or right (*e.g.*, #3, 8) or with more (*e.g.*, #2, 7, 8, 9) or less (*e.g.*, #3, 6) dispersion than the controls. Ordinary tests for the significance of differences between means, or between standard deviations in the frequency distributions among the three groups of 20 even within these single series, yielded, not uncommonly, probabilities ranging from the 5% to well less than 0.1% level. There was no suggestion that these differences could be explained on the basis of any continuous trend in behavior during the experimental period of a series. In fact, this last possibility was greatly reduced by having each sample of twenty composed of two groups of ten separated by intervening runs under other conditions.

It seemed quite apparent that if a *bona fide* response occurred to either the earth's magnetic field or the experimentally imposed ones, the response could not be simple and invariable. Consequently, analyses of the data involved chiefly three types of values: (a) mean direction and degree of turning; (b) total dispersion as a measure of right and left turning about the zero axis; and (c) standard deviation as a measure of dispersion relative to whatever was the mean path of the given series. The forms of frequency distributions were also always inspected.

(*A*) *Mean path of snails:* Using all data, it became quickly evident that there was a daily rhythm in the average degree of turning of the emerging snails, the animals moving nearly straight ahead at 5 AM and turning increasingly to the left until noon. Thereafter, they turned progressively less, to a second minimum of turning about 7 PM. The mean paths for the snails exposed to the N–S and E–W experimental magnetic fields, and for the controls are plotted as a function of hour of the day in Figure 4A. Indicated also are standard errors of the means for the combined three groups for selected hours. In Figure 4B are illustrated the differences, hour by hour, between the path of the controls and the snails in each of the two experimental magnetic fields. Using all 1128 available differences between experimental and control animals, a mean of -0.0341 ± 0.0104 was obtained. This indicated that the presence of a magnet results in increased left-turning over controls ($P < .005$).

There was no statistically significant difference between the effect of the N–S field (-0.0347) and E–W one (-0.0336). It is, however, suggestive that the 3.2% greater effect of the N–S field is correlated with the actual 12% greater horizontal intensity of the experimental N–S over the experimental E–W field, due to the vectorially additive effect of the earth's natural field in the former experimental condition.

In view of the evident daily rhythm in the mean path observed, together with the suggestion from Figure 4B that increase in strength of magnetic field in the early morning hours yields greater *right* turning, an examination of the effect of the magnetic fields for the hours 7 AM through 9 PM was made. This gave even more decisive indication of increased left-turning in response to the experimental

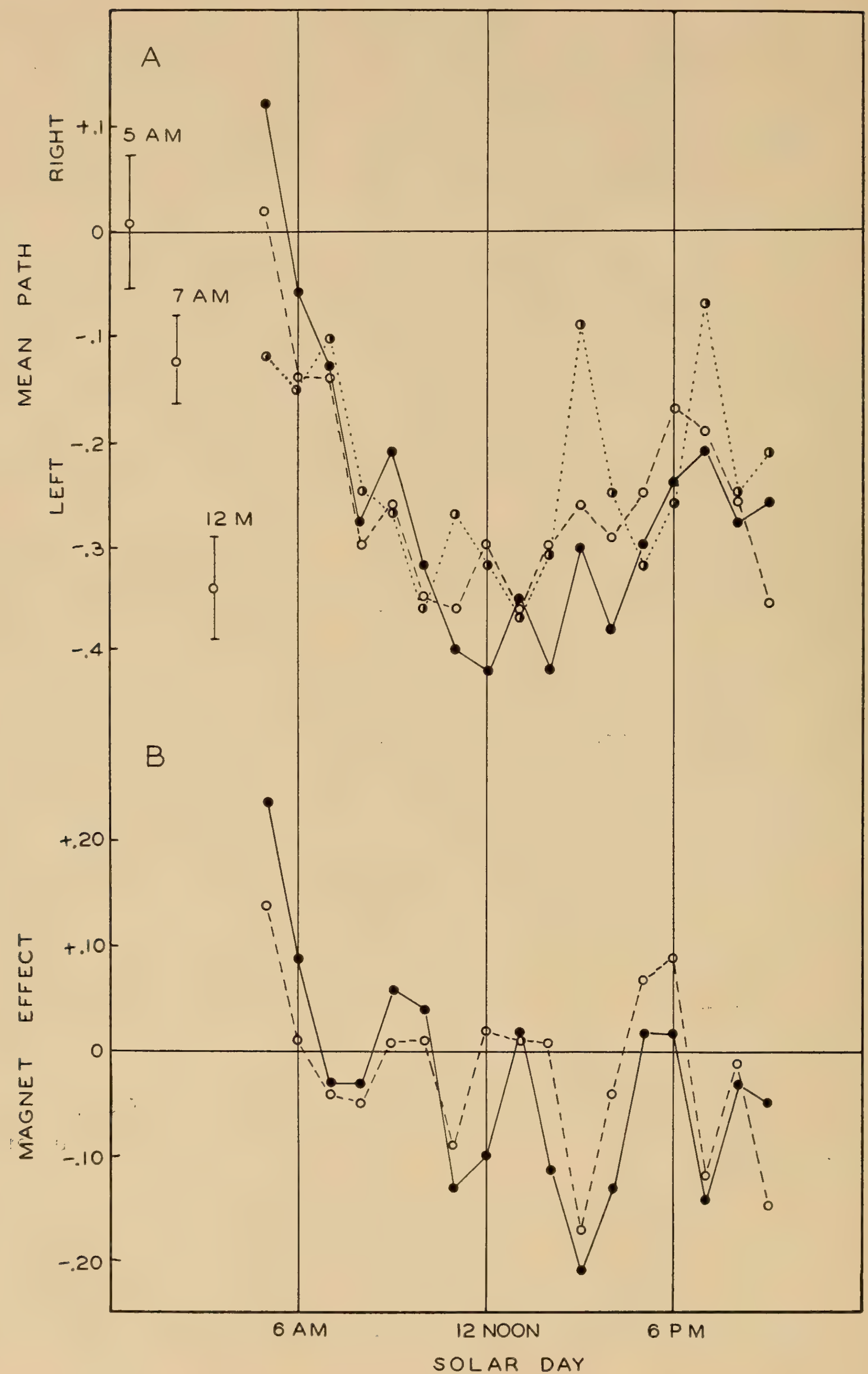

FIGURE 4. A. Mean paths of the snails in the E–W magnet field (dashed lines), in the N–S magnet field (solid line), and control snails (dotted lines) as a function of hour of the solar day. Standard errors of means for all snails are shown for three times of day. B. The difference of mean paths of snails in the E–W magnet field (dashed line) and N–S magnet field (solid line) from the paths of the control snails in the same series.

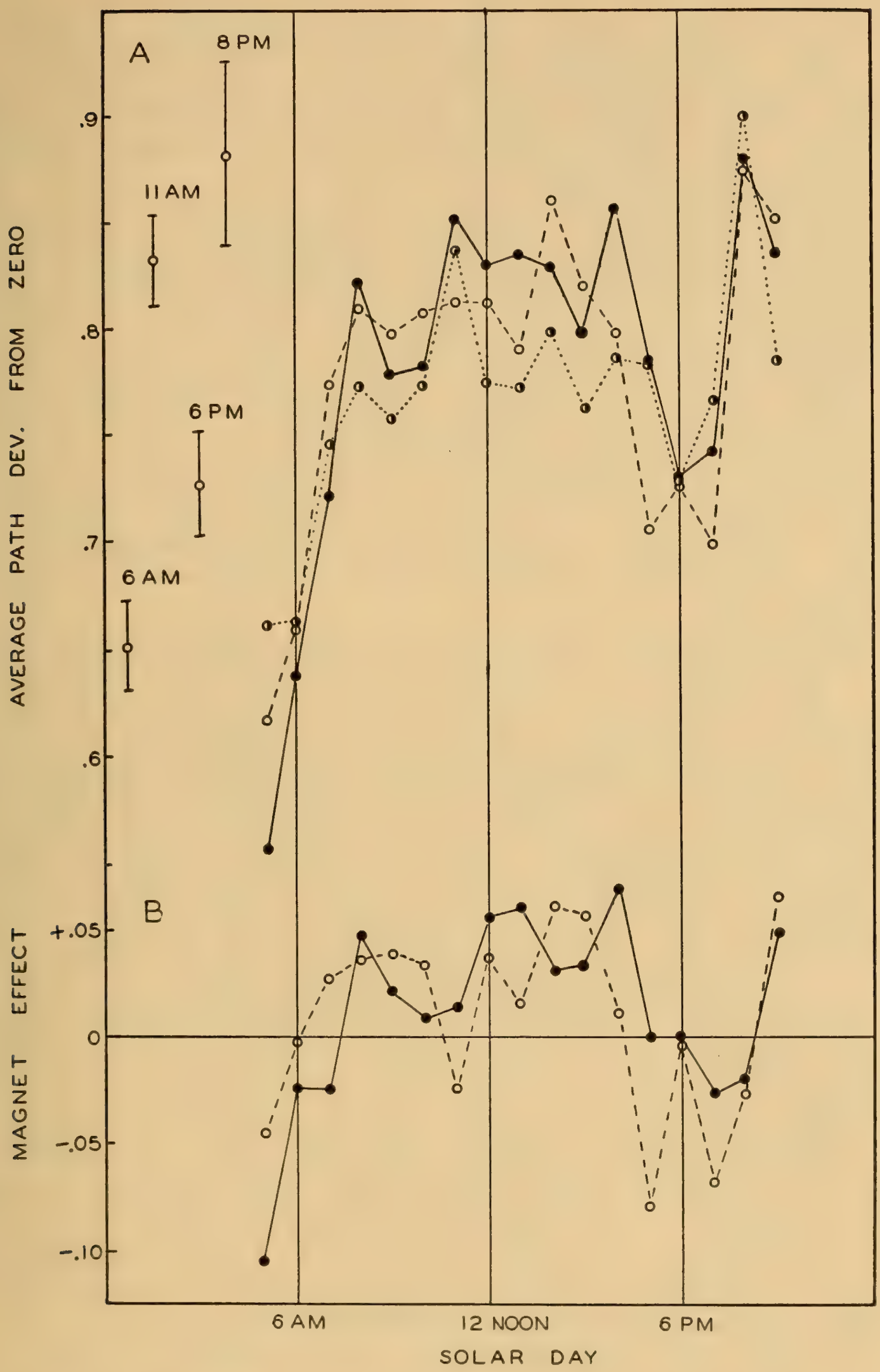

FIGURE 5. A. Mean dispersion of experimental and control snail paths from the zero sector as a function of hour of day. Standard errors of means from all snails are shown for four times of day. B. Difference between experimental snails and controls as a function of time of day. See Figure 4 legend for key.

magnetic fields ($P < .001$). Also, for the 3 PM hour alone the effect of the increased magnetic field strength was highly significantly different from zero ($t = 3.64$; $N = 84$). These probabilities, which leave no reasonable doubt as to a response to the magnet, are found despite highly significant fluctuations of magnetic response of lunar-day frequency which contribute greatly to the variability of the response (Brown, Webb and Brett, 1960).

(*B*) *Mean dispersion of paths from zero:* Inspection of the frequency distributions of the mean snail paths as a function of hours of the day, indicated an increasing bimodality of the distribution of the paths, through a maximum degree of bimodality near noon. A consequence of this is clearly apparent in the form of a daily fluctuation in average dispersion (Fig. 5A). Standard errors for selected hours are shown. A broad maximum is centered over noon, and a second maximum occurs at night. There is also evident a daily rhythm in the difference between mean dispersions of control and experimental animals (Fig. 5B). For a 9-hour period centered at noon, the mean dispersion of the animals as the average for the two magnetic fields was $7.55 \pm 1.96\%$ ($N = 364$) greater than that of the controls. These results suggest, further, that the effect of both magnet positions in early morning and early evening is to reduce dispersion even below that of the controls within the same series.

(*C*) *Standard deviation of paths:* The next analysis was of the fluctuations in standard deviation of paths. It was clear that there was a daily fluctuation in this parameter. This is illustrated in Figure 6A. The significance of this cycle can be seen from the two standard errors included. In this parameter, as in the others, the frequency distributions suggested increasing bimodality for the data obtained over the middle of the day. However, at those times of day, 8–12 AM and 8 and 9 PM, when standard deviations are relatively lower than might be expected in terms of total dispersion (compare Figs. 5A and 6A), the population of values more strongly favors one of the two centers in the bimodal frequency distribution. Figure 6B illustrates the hour-by-hour difference between the control snails and the snails in the experimentally augmented magnetic fields. The daily pattern of effect of the imposed magnetic fields upon altering the standard deviation of paths selected appears to possess at least three maxima. With all the data from the 17 hours of the day, the standard deviation appeared increased by the magnets, though not highly significantly ($P < .05$). For the period 6 AM through 4 PM alone, the statistical significance increased substantially ($P < .01$). However, that an influence of the magnetic fields is being reflected in this parameter is suggested even more strongly from the similarity of the mean daily pattern of effect for the two magnetic orientations, N–S and E–W ($r = 0.72$) ($N = 17$), though the significance of this correlation is obviously tempered somewhat by the fact that there was a common control group for the two experimental groups.

(*D*) *Frequency distribution of magnet responses, relative to hours of day:* In view of the clear indication from the preceding analyses that the imposed magnetic fields effect to various extents either of two types of response, right or left turning, it seems reasonable to presume that (1) the small, but statistically highly significant, predominance of left turning especially between the hours 7 AM and 9 PM, and (2) the clear suggestion of right turning at 5 and 6 AM are simply residuals, a consequence of failure of one response to be cancelled exactly by the

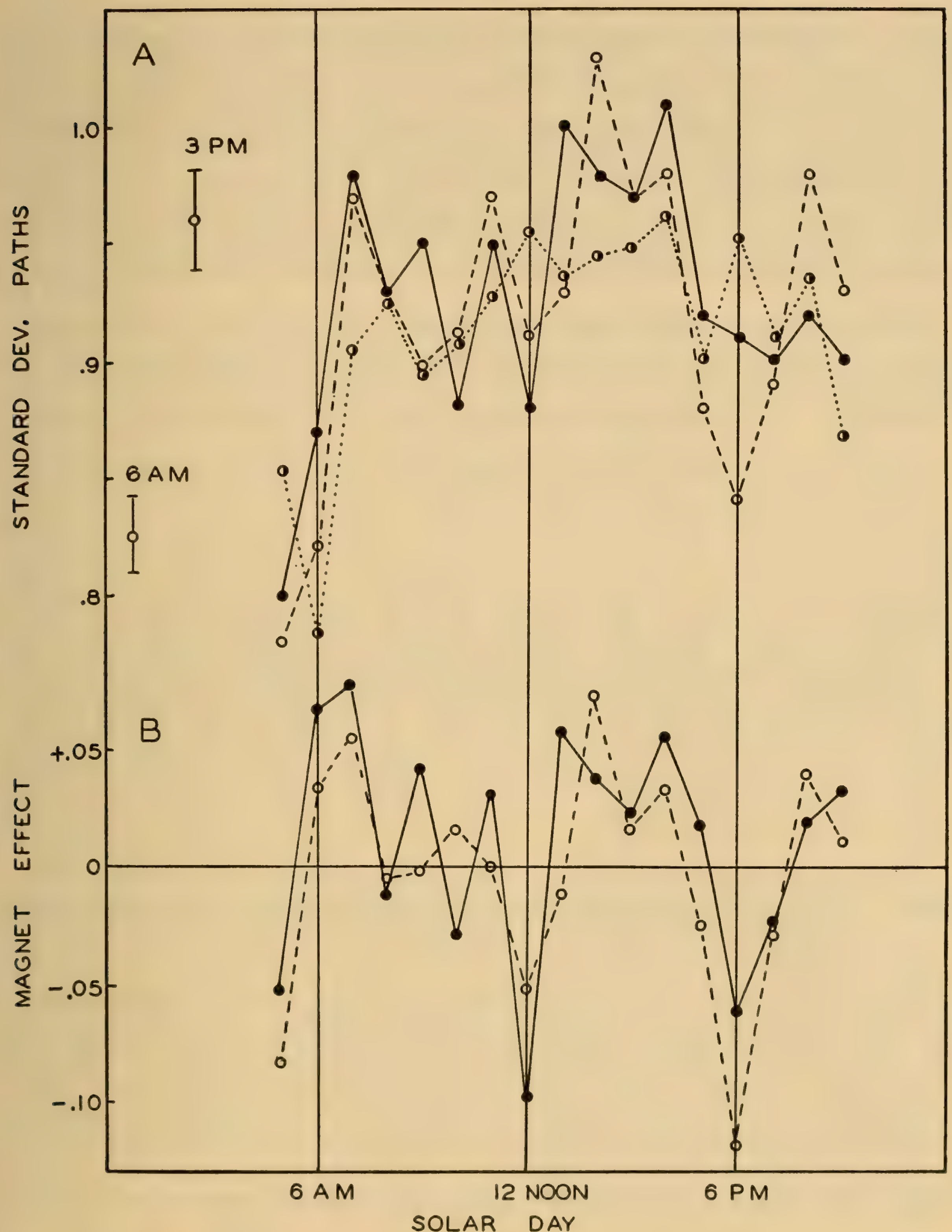

FIGURE 6. A. Standard deviation of experimental and control snail paths, as a function of hour of day. B. Difference between experimental snails and controls as a function of time of day. See Figure 4 legend for key.

other. To cast further light upon this aspect of the problem, frequency distributions of the differences obtained between experimental animals and the controls in the same series are shown as a function of hour of the solar day in Figure 7. From the general dissimilarity of nearly all these to normal distributions, and the strong tendency towards bimodal distributions (see especially 9 AM through 4 PM), these suggest that the organismic response to the imposed magnetic fields is not only real, but substantially larger than was apparent from the simple study of the pooled hourly data. The actual response appears normally to amount to magnetic-induced turning through an average of 0.3 to 0.4, or more, of a sector unit, or a mean turning of the order of 8–10° during the snail passage in a few seconds over the 3-cm. course.

Further inspection of the distributions suggests that a response to the imposed magnet occurs also as a deviation from a mean degree of turning characteristic of the particular hour of the solar day. This is most evident in the 3 PM and 9 PM distributions. It is also suggested for the 5 and 6 AM hours, when the mean

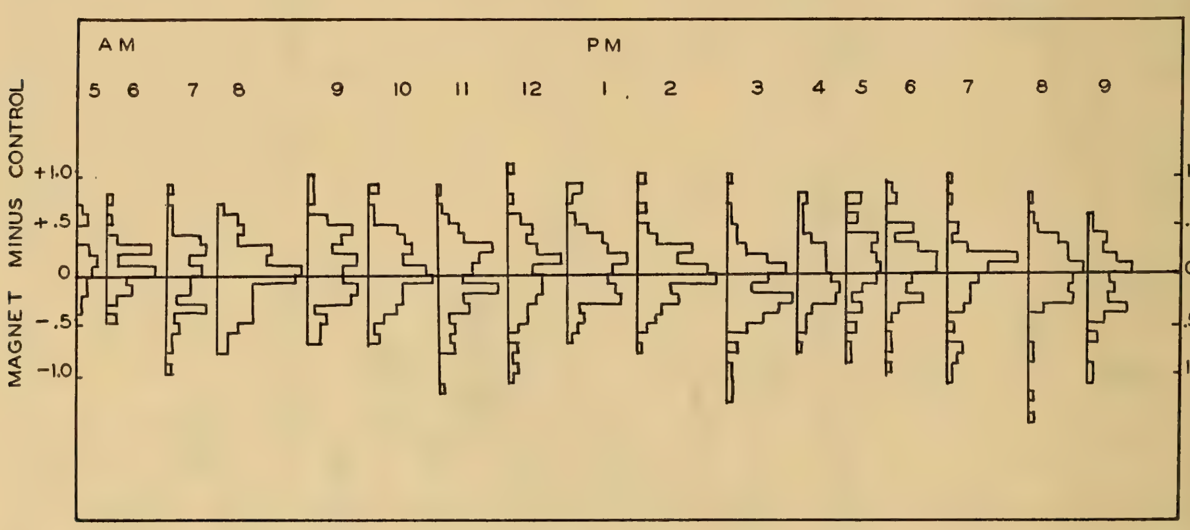

FIGURE 7. Forms of frequency distributions of the differences between all experimental snail paths and control snail paths, as a function of hour of the solar day.

turning of controls is near zero and the response to the magnet is predominantly that of turning to the right. It appears also evident that the mean effectiveness of the two experimental magnetic fields passes through minima at 8 AM, 2 PM, and 7 to 8 PM, as indicated by the reduction in the bimodality at these times. This changing pattern of frequency distributions through the day suggests the presence of two major daily patterns of oscillation in the extent of the response to the experimentally increased magnetic fields, with one pattern essentially the mirror-image of the other, and with cross-over points at these times of minimal response.

Discussion

It is apparent from this study that in the constant symmetrical experimental field the amount of turning of snails is a function of the time of day, and that a daily fluctuation is found in both the mean amount of turning, ignoring sign, and in the mean path of the snails taking sign into account. This is apparent for all snails, both those in the earth's natural magnetic field and in the imposed fields where the field strength is increased about 10-fold with the direction of magnetic lines of force being left either in the same direction as the earth's, or at right angles to this. The three groups considered as three samples showed remarkable mean similarities as functions of hours of the day, though commonly differing very widely from one another in any individual series (see Fig. 3). This similarity indicated that the amount of right or left turning, or dispersion of paths from zero, was not determined primarily by the direction of the field or by its fluctuations in strength.

Hence, it must be concluded that the response is predominantly a klinokinesis, or a turning relative to any initial compass direction, either clockwise or counterclockwise, as a function of time of day. Of the various possibilities of the factors concerned in the response, three are immediately apparent. (1) The response involves a rate of turning relative to the diffusing light source above and slightly ahead of the path of the snail. This might be interpreted as a move on the part of the snail to assume a particular angular relationship between the long-axis of its body (light-compass relationship) and the artificial gigantic "sun" as a function of the time of solar day; (2) the turning of snails involves a torsional orientation in response to the magnetic field itself as a function of time of day; (3) the orientational response may not be due to any external factor directly, but simply to differential bilateral activity of bodily orientation mechanisms. Or, possibly any two or all might be involved and contribute jointly to the results. However, it is evident from this study that just as would be expected were the response normally one of klinokinesis in response to the magnetic-field, so the klinokinesis can be highly significantly modified through experimentally increased magnetic flux as a function of time of solar day. There also remains an additional possibility, namely, that any light-compass orientation of the snails is, in turn, regulated through an orientation to magnetic field.

Support for the concept that the normal turning of the snail is importantly an orientation in response to magnetic field itself may be seen first in Figure 5. When the dispersion is least in the earth's magnetic field, the effect of increasing magnetic flux is to reduce it still more, and when dispersion is large in the earth's field, the magnet increases it still more. Comparably, as Figure 4 indicates, when left-turning is high in the earth's natural field the magnet increases it, and when it is low, appears to effect turning in the opposite direction, to the right. In a general manner, but slightly more complexly, the relationships of Figure 6 also give a similar kind of support for the view of an important role of the normal earth's field in snail orientation. The effect of the experimentally augmented field is to bring about either further increased, or decreased, size of standard deviation, depending upon which is normally the predominant response characteristic of the time in the daily cycle.

It is very interesting, also, to compare the two aspects of magnetic orientation, left-turning and bimodality of distribution about a mean path, to the two signs of oxidative metabolic fluctuations of *Nassarius* about a mean daily non-inverting fluctuation. Both the non-inverting and inverting components in these metabolic fluctuations appear clearly to be responses to unidentified barometric pressure correlates (Brown, Webb and Brett, 1959). This suggests an intimate relationship between the mechanisms of temporal and spatial orientation in the snails and points to the possibility that the experimentally augmented magnetic field has in part simply increased the strength of whatever orientational physiological mechanism chanced to be dominant at the time, through a generalized influence upon the mechanism of cellular oxidative energy transformations. For this effect, the magnetic field would need to possess no spatial orientational feature, *per se*. But while this effect might account for the induced increases in standard deviation or increased turning, it could scarcely account for those times of improved precision of orientation by reduction of turning below that of the controls. The last appears more rationally accountable in terms of the concept that the sharp and stronger the magnetic field, the more decisive whatever organismic responses are characteristic of that time of day to it.

Summary

1. The orientation of snails in a constant, symmetrical field was studied over a two-month period, June 28 through August 29, 1959, at various hours of the day between 5 AM and 9 PM.

2. The orientation of snails in the earth's natural magnetic field was compared throughout the study with the orientation of snails subjected to a 9- to 10-fold increase in field strength, with fields both parallel and at right angles to the earth's natural field.

3. A daily rhythm in the direction and average amount of turning was found in the snails; the mean paths of those in the two (N–S; E–W) experimentally augmented magnetic fields were statistically significantly to the left of the controls, particularly between the hours 7 AM through 9 PM.

4. The mean amount of turning, whether clockwise or counterclockwise (klinokinesis), in the experimental magnetic field was also increased significantly over that of controls in solely the earth's field, and similarly exhibited a daily rhythm.

5. Certain similarities between the orientational responses to the magnetic fields and earlier described exogenous metabolic fluctuations in constant conditions, suggest a relationship between them.

6. Evidence is advanced supporting the hypothesis that the orientation of snails normally includes a true response to the earth's magnetic field.

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